

# Hard photodisintegration of a proton pair in $^3\text{He}$

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## Abstract

Hard photodisintegration of the deuteron has been extensively studied in order to understand the dynamics of the transition from hadronic to quark–gluon descriptions of the strong interaction. In this Letter, we discuss the extension of this program to hard photodisintegration of a  $pp$  pair in the  $^3\text{He}$  nucleus. Experimental confirmation of new features predicted here for the suggested reaction would advance our understanding of hard nuclear reactions. A main prediction, in contrast with low-energy observations, is that the  $pp$  breakup cross section is not much smaller than the one for  $pn$  break up. In some models, the energy-dependent oscillations observed for  $pp$  scattering are predicted to appear in the  $\gamma^3\text{He} \rightarrow pp + n$  reaction. Such an observation would open up a completely new field in studies of color coherence phenomena in hard nuclear reactions. We also demonstrate that, in addition to the energy dependence, the measurement of the light-cone momentum distribution of the recoil neutron provides an independent test of the underlying dynamics of hard disintegration.

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## 1. Introduction

We define the hard photodisintegration of a nucleon pair as a process in which a high energy photon is ab-

sorbed by a nucleon pair leading to pair disintegration into two nucleons with transverse momenta greater than about  $1 \text{ GeV}/c$ . In this process the Mandelstam parameters  $s$ , the square of the total energy in the c.m. frame, and  $t \approx u$ , the four-momentum transfers from the photon to the nucleons, are large. With  $s$  above the resonance region, and  $-t, -u \geq 1 \text{ GeV}^2$ , the kinemat-

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ics are in the transition region, in which the short distance scales probed might make it appropriate to formulate the theory in terms of quark and gluon rather than hadronic degrees of freedom.

High-energy photodisintegration of a nucleon pair provides an efficient way to reach the hard regime. To obtain the same  $s$  in  $NN$  scattering, one needs an incident nucleon lab momentum about a factor of two larger than that of the photon. Photodisintegration of a  $pn$  pair, the deuteron, has now been extensively measured at high energies [1–8]. In this work, we investigate a related process, the hard photodisintegration of a  $pp$  pair, in the  ${}^3\text{He}$  nucleus.

Deuteron photodisintegration cross sections are available for photon energies up to 5 GeV (but only 4 GeV at  $\theta_{\text{c.m.}} = 90^\circ$ ) [1–5] including, for energies up to 2.5 GeV, “complete” angular distributions [6,7] and recoil polarizations [8]. Fig. 1 shows the measured energy dependence of  $s^{11}(d\sigma/dt)$  for  $90^\circ$  c.m. The quark counting rule prediction [9–11], that this quantity becomes independent of energy, is observed clearly. High-energy deuteron photodisintegration cross sections at other angles are also in good agreement with scaling once  $p_T \geq 1.3$  GeV/ $c$ .

The good agreement of the data with the quark counting rule prediction contrasts with observations [12,13] that pQCD underestimates cross sections for intermediate energy photoreactions—examples include the deuteron elastic form factor [14], meson photoproduction [15] and real Compton scattering [16]. Thus, it seems that although the observation of the scaling in a given reaction indicates the onset of the quark–gluon degrees of freedom, the appropriate underlying physics has a mixture of perturbative and nonperturbative QCD aspects. A variety of theoretical models exist for deuteron photodisintegration which explicitly account for quark–gluon degrees of freedom in the reaction with an attempt to incorporate the nonperturbative QCD effects.<sup>1</sup> Hidden color degrees of freedom of the nucleus might play an important role in determining the normalization of hard-scattering nucleon amplitudes [14,18].

The reduced nuclear amplitude (RNA) formalism [19] attempts to incorporate some of the soft physics

not described by pQCD by using experimentally determined nucleon form factors to describe the gluon exchanges within the nucleons. It neglects diagrams in which gluon exchanges between the nucleons lead to noncolor singlet intermediate “nucleon” states, diagrams which might be important in pQCD calculations. Ideally, the RNA calculation should be normalized to the scaling behavior at asymptotic energies, where both yield the same result. In practice, the normalization must be to data, but at energies sufficiently large. An estimate of the necessary photon lab energy is obtained by requiring the momentum transfer to each nucleon to be above 1 GeV, which yields [20]

$$\frac{1}{2}M_d E_\gamma \left[ 1 - \sqrt{\frac{2E_\gamma}{M_d + 2E_\gamma}} |\cos \theta_{\text{c.m.}}| \right] \geq 1 \text{ GeV}^2. \quad (1)$$

The two-quark coupling (TQC) model [21] is based on the idea that the photon interacts with a pair of quarks being interchanged between the two nucleons. An analysis of this hard interaction then shows that the reaction has leading kinematic dependences proportional to nucleon form factors, taken to be the dipole form factor, to the fourth power times a phase space factor times a propagator,  $(s - \Lambda^2)^{-1}$ , where  $\Lambda \approx 1$  GeV. There is no absolute normalization predicted by the model; instead it is normalized to the data at one point. The formula manages to largely reproduce the energy and angle dependences of hard deuteron photodisintegration, for  $E_\gamma > 2$  GeV, once this one normalization parameter is fixed. With the propagator  $(s - \Lambda^2)^{-1}$ , instead of the factor  $p_T^{-2}$  in the similar RNA formula, the energy and angle dependences are softened, improving the agreement with the data.

The quark–gluon string model (QGS) [22] views the reaction as proceeding through three-quark exchange, with an arbitrary number of gluon exchanges. The cross section is evaluated using Regge theory techniques, and is sensitive to the Regge trajectory used. While Regge theory has been shown to be an efficient description of high energy, small- $t$  reactions, it has not typically been applied to the large momentum transfers being discussed in this Letter. The best fit of the data is obtained in a calculation that uses a nonlinear trajectory, as opposed to the more familiar linear trajectory.

<sup>1</sup> Note that to date there are no successful meson-baryon calculations for the high energy data. For a recent review, see [17].

The QCD hard rescattering model (HRM) [23] assumes that the photon is absorbed by a quark in one nucleon, followed by a high momentum transfer interaction with a quark of the other nucleon leading to the production of two nucleons with high relative momentum. Summing the relevant quark rescattering diagrams demonstrates that the nuclear scattering amplitude can be expressed as a convolution of the large angle  $pn$  scattering amplitude, the hard photon–quark interaction vertex and the low-momentum nuclear wave function. Since the  $pn$  hard scattering amplitude can be taken from large angle  $pn$  scattering data, the HRM model allows calculation of the absolute cross section of the  $\gamma d \rightarrow pn$  reactions using no adjustable parameters.

Fig. 1 demonstrates the comparison of the calculations based on the models discussed above with the available data for deuteron disintegration at  $\theta_{c.m.} = 90^\circ$ . RNA, TQC and QGS calculations require nor-

malization to the data. The HRM does not require such a normalization factor, however, the poor accuracy of hard-scattering  $pn$  data restricts the overall accuracy of the calculation to the level of 20%—this is shown as an error band in the figure. Each of the models describes some part of the data, but no model describes all of the data. Therefore further studies to advance our understanding of hard photodisintegration reaction dynamics are needed.<sup>2</sup>

## 2. Breaking a $pp$ pair

In the present Letter we suggest a new venue for studying the dynamics of hard nuclear reactions. We propose to extend the studies of hard photodisintegration reactions from the  $pn$  system of the deuteron to the  $pp$  system. Namely, we propose the investigation of the reaction  $\gamma {}^3\text{He} \rightarrow pp + n$  in which we define the measurement conditions so that the neutron in  ${}^3\text{He}$  can be considered, at least approximately, as a static spectator, while two protons are produced at  $90^\circ$  in the c.m. frame of the  $\gamma pp$  system.<sup>3</sup>

The *advantage* of this program is that although many of the considered models do not predict the absolute cross section, still they can predict the relative cross section of the hard  $\gamma(pp) \rightarrow pp$  reaction as compared to the  $\gamma(pn) \rightarrow pn$  reaction. The  $pn$  data from the deuteron already exist, and will be used in this Letter to provide an overall normalization so that absolute  $\gamma {}^3\text{He}$  cross sections, rather than just the  $s$  dependence of the  $\gamma pp$  cross section, can be predicted. The nucleus  ${}^3\text{He}$  has been used successfully to observe the absorption reaction  $\pi^- pp \rightarrow np$  [25] at much lower energies than appear here. Thus the use of  ${}^3\text{He}$  as a source of a  $pp$  target has a successful history.<sup>4</sup>

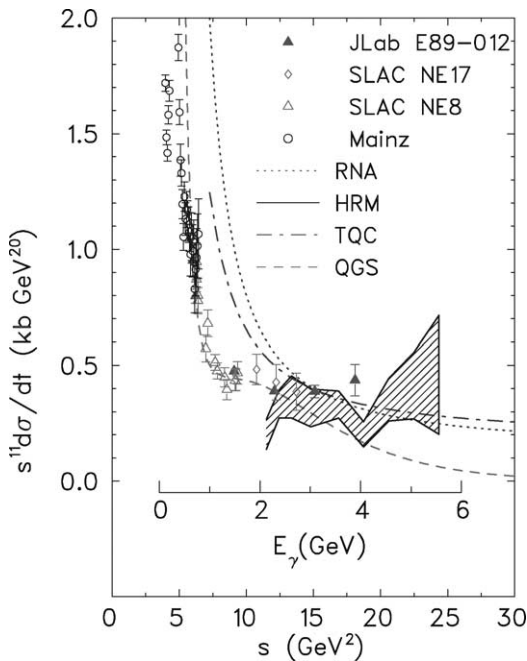


Fig. 1. The energy dependence of  $s^{11}(d\sigma/dt)$  for  $90^\circ$  c.m. photodisintegration of the deuteron. The HRM result is shown as a shaded band. The QGS calculation is the long dashed line. The RNA result is the dotted line, normalized to the data point at 3 GeV. The dot dash line shows the TQC formula, normalized to the 3 GeV data point. The experimental data is labeled by the laboratory and the experiment number.

<sup>2</sup> We also note a recent study of deuteron photodisintegration in a constituent quark model [24].

<sup>3</sup> This can be done experimentally by selecting events in which the reconstructed missing neutron momentum is less than 100 MeV/c.

<sup>4</sup> Measurements of the  $pn$  break up in  ${}^3\text{He}$  are also possible, and would remove some uncertainty in the nuclear physics aspects of the calculation. For example, sensitivity to the high momentum component of the nuclear wave function would be reduced.

**RNA model** In the RNA approach [19], the differential cross section is proportional to the squares of form factors, one for each nucleon, evaluated at the momentum transfer for that nucleon in the weak-binding limit. The remainder, the “reduced” cross section, is assumed to be independent of the substructure of the nucleons. This gives

$$\frac{d\sigma}{dt} \simeq F_{N_1}^2(-t_1) F_{N_2}^2(-t_2) \left. \frac{d\sigma}{dt} \right|_{\text{reduced}}, \quad (2)$$

for the process  $\gamma(N_1 N_2) \rightarrow N_1 N_2$ , with  $t_i$  the square of the four-momentum transfer to nucleon  $N_i$ . The ratio of cross sections for  $\gamma(pp) \rightarrow pp$  and  $\gamma(pn) \rightarrow pn$  is then given by the ratio of nucleon form factors squared,  $F_p^2(-t_N)/F_n^2(-t_N)$  ( $t_N \approx t/2$ ), times the ratio of the reduced cross sections. The ratio of form factors can be obtained from data for  $G_M$  and  $G_E$  [26]; we use the leading twist form factor  $F_1$  for each nucleon, for which the ratio  $F_{1p}/F_{1n}$  is approximately  $-2$ . The ratio of reduced cross sections is taken to be 4, the square of the charge ratio. These estimations yield  $\gamma(pp) \rightarrow pp$  cross section approximately 16 times larger than the RNA prediction for  $\gamma d \rightarrow pn$  cross section. The absolute normalization for the  $\sigma_{\text{RNA}}(\gamma(pp) \rightarrow pp)$  can be obtained from comparison of  $\sigma_{\text{RNA}}(\gamma d \rightarrow pn)$  with available data.

To estimate the cross section of  $\gamma^3\text{He} \rightarrow pp + n$ , we shall multiply the above estimates of the cross section of the disintegration of the  $pp$  pair,  $\sigma(\gamma(pp) \rightarrow pp)$ , by a factor that combines the relative probability of a  $pp$  pair in the  $^3\text{He}$  wave function with a correction from the integration over the slow neutron’s momentum. Note that no new normalization with the experimental data is needed, since we use the normalization factors obtained from the comparison of the  $\gamma d \rightarrow pn$  cross sections with the data.

To estimate this factor we observe that in RNA the amplitude results from the  $pp$  wave function at small separations. Therefore, as a simple estimate we use the parameter  $a_2(A)$  which characterizes the probability of two-nucleon correlations in the nuclear wave function,  $a_2(A=3) \approx 2$  [27,28], multiplied by  $1/3$ , which accounts for the relative abundance of  $pp$  pairs in the two-nucleon short-range correlation. The integration of the neutron momentum up to  $100 \text{ MeV}/c$  leads to an additional factor of  $1/2$ . Thus, these estimations yield an overall factor of  $\approx 1/3$  by

which  $\sigma(\gamma(pp) \rightarrow pp)$  should be scaled in order for it to correspond to the  $\gamma^3\text{He} \rightarrow pp + n$  cross section. The overall factor of  $1/3$  is a conservative estimate; the inclusion of three-nucleon correlations in  $^3\text{He}$  would increase this factor. Thus, in the RNA approach,  $d\sigma(\gamma^3\text{He} \rightarrow pp + n)/d\sigma(\gamma d \rightarrow pn) = 16/3$ .

**TQC model** Estimates for the  $\sigma(\gamma(pp) \rightarrow pp)$  to  $\sigma(\gamma(pn) \rightarrow pn)$  cross-section ratio in the TQC model are underway [21]. We expect the same  $^3\text{He}$  correction factor of  $1/3$  that we apply to the RNA model.

**QGS model** In the QGS model, since the breakup cross section is defined by the effective Regge trajectory, we would expect the Regge trajectories to be similar, so the  $\sigma(\gamma(pn) \rightarrow pn)$  and  $\sigma(\gamma(pp) \rightarrow pp)$  cross sections are of similar magnitude [31]. We assume that this is multiplied by the same  $^3\text{He}$  correction factor of  $1/3$  that we apply to the RNA model.

**HRM model** The differential cross section within the HRM model is [29]:

$$\begin{aligned} \frac{d\sigma}{dt d^3 p_n} &= \left(\frac{14}{15}\right)^2 \frac{8\pi^4 \alpha_{EM}}{s - M_{^3\text{He}}^2} \frac{d\sigma^{pp}(s_{pp}, t_N)}{dt} \\ &\times \frac{1}{2} \left| \sum_{\text{spins}} \int \Psi^{^3\text{He}}(p_1, p_2, p_n) \sqrt{M_N} \frac{d^2 p_{2T}}{(2\pi)^2} \right|^2, \end{aligned} \quad (3)$$

where  $s = (P_\gamma + P_{^3\text{He}})^2$ ,  $t = (P_p - P_\gamma)^2$ ,  $s_{pp} = (P_\gamma + P_{^3\text{He}} - P_n)^2$ , and  $t_N \approx (1/2)t$ . The  $pp$  elastic cross section is  $d\sigma^{pp}/dt$ . The momentum of the recoil neutron is  $p_n$ . In the argument of the  $^3\text{He}$  nuclear wave function,  $\vec{p}_1 = -\vec{p}_2 - \vec{p}_n$  and  $p_{1z} \approx p_{2z} \approx -p_{nz}/2$  near  $90^\circ$ . The  $pp$  scattering cross section was obtained from a fit to the existing  $pp$  data [30]. The overall factor  $(14/15)$  is obtained based on the quark-interchange model of hard  $NN$  scattering utilizing the  $SU(6)$  wave function of nucleons. This introduces an uncertainty in the estimates of the cross section at the level of 10–20%. The  $^3\text{He}$  wave function is that of Ref. [27], obtained by solving the Faddeev equation with a realistic  $NN$  potential. The predicted cross section is made singly differential by integrating over neutron momentum, up to  $100 \text{ MeV}/c$ .

Fig. 2 shows predictions based on the models considered above for  $90^\circ$  two-body break-up kinematics. The  $\gamma^3\text{He} \rightarrow pp + n$  cross section has been integrated over the neutron momentum up to  $100 \text{ MeV}/c$ .

These predictions ignore nuclear corrections due to the soft rescattering of the nucleons in the final state. We argue here that they are only small corrections in the kinematics discussed. For energetic protons rescattering on the slow spectator neutron, the mean squared value of the momentum transferred during the soft rescattering is  $200\text{--}250 \text{ MeV}^2/c^2$ . Restricting the neutron momenta to  $\leq 100 \text{ MeV}/c$  significantly reduces the soft-rescattering. This effect can be reliably calculated within the eikonal approximation. Preliminary estimates yield 5–10% corrections in the range of  $40\text{--}90^\circ$  c.m. angles.

Another correction is due to primary reactions on the  $pn$  pair, with subsequent soft  $pn \rightarrow np$  charge-exchange rescattering of the energetic neutron with the slow spectator proton. In the energy range of this study, the charge-exchange soft rescattering is suppressed by a factor of  $1/s$  as compared to the non-charge-exchange soft rescattering, and results in only a

1–2% correction. This estimate takes into account the larger probability of  $pn$  than  $pp$  pairs in  $^3\text{He}$ .

It is important to note that the models considered above predict a sizable cross section for the break up of the  $pp$  pair, larger than that for the  $pn$  pair, for two of the three models shown. This prediction is rather striking since at low energies it is well known [32] that photodisintegration of the  $pp$  system is suppressed as compared to  $pn$ .

Within a mesonic description of the interaction, the  $90^\circ$  break up of a  $pp$  pair will be significantly suppressed as compared to  $pn$  since for the  $pp$  pair the exchanged mesons are neutral and do not couple to the photon. In a quark–gluon picture, the exchanged particles are quarks, and the suppression will be absent. As a result an experimental observation of a larger cross section for the  $pp$  break-up reaction will be an indication of the dominance of quark–gluon dynamics in the reaction.

### 3. Oscillations with energy

The possibility that the final-state high- $p_T$  proton pair is formed due to the hard interaction of the two outgoing protons might produce energy oscillations, as seen in the  $pp$  cross section. The quark counting rule predicts  $(d\sigma/dt) \sim s^{-10}$  for high-energy, large-angle  $pp \rightarrow pp$  elastic scattering. The  $pp$  elastic data are globally consistent over a large number of decades with the power law [30,33]. However, it was already noted in 1974 [34] that a more detailed examination of the data indicated significant deviations from scaling. The deviations are known as “oscillations” and were interpreted as resulting from interference between the pQCD amplitude and an additional nonperturbative component.

Ralston and Pire [35] suggested that the interference is between a small size configuration pQCD scattering and an independent scattering of *all* valence quarks discussed by Landshoff [36], governed by the so-called chromo-Coulomb phase. Brodsky and de Teramond [37] suggested that the oscillations are due to the presence of two broad resonances (or threshold enhancements) which interfere with the standard pQCD amplitude. For a review of wide-angle processes, see [38].

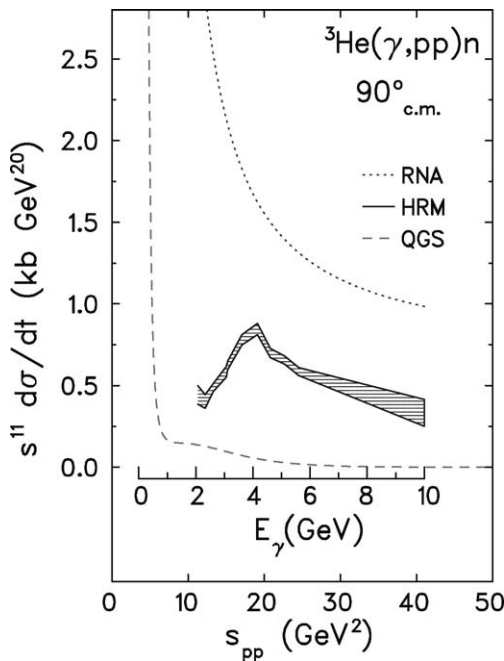


Fig. 2. Predictions for  $\gamma^3\text{He} \rightarrow pp + n$  at  $\theta_{\text{c.m.}} = 90^\circ$ . The line types are the same as for Fig. 1. The horizontal scale is  $s$  for the  $\gamma pp$  system; the photon energy scale is also shown.

Whatever is the correct interpretation of the oscillation, if the hard two-body break-up reaction proceeds through the hard interaction of two protons, similar oscillations could be seen in the  $\gamma^3\text{He} \rightarrow pp + n$  cross section, normalized by a factor of  $s^{11}$ , as a function of the incident photon energy, in the same region of  $s$  where  $pp$  oscillations are observed. Fig. 3 compares the energy dependence of  $pp$  cross section with that of  $\gamma^3\text{He} \rightarrow pp + n$  cross section at  $90^\circ \gamma - (pp)$  center of mass scattering ( $-t/s_{pp} \approx 1/2$ ), calculated within the HRM model, which assumes the dominance of the contribution of hard  $pp$  rescattering in the photodisintegration reaction. Note that according to Eq. (3) the  $pp$  cross section that enters in the  $\gamma + ^3\text{He} \rightarrow pp + n$  cross section is defined at  $s_{pp}$  and  $t_N \approx t/2$ . As a result, in Fig. 3 one compares with  $pp$  cross sections defined at  $\approx 60^\circ$  ( $-t_N/s \approx 1/4$ ) [30]. In contrast to the situation displayed in Fig. 3, the precision of the

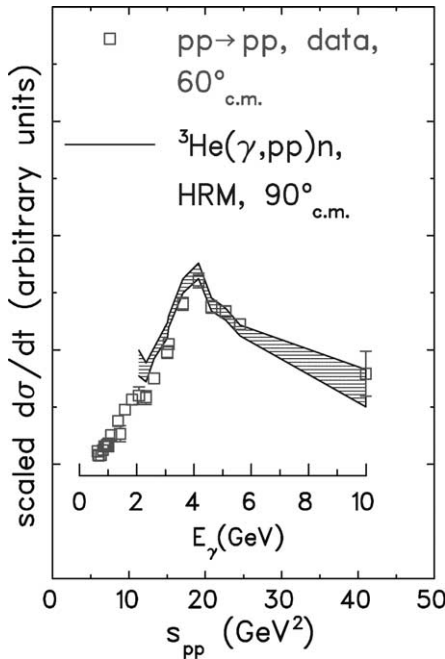


Fig. 3. Energy dependence of the  $\gamma^3\text{He} \rightarrow pp + n$  cross section predictions multiplied by  $s^{11}$ , compared with the energy dependence of the  $pp \rightarrow pp$  cross section multiplied by  $s^{10}$  and rescaled by an overall constant, to emphasize the similarity in the energy dependences. The horizontal scale is  $s$  for the  $\gamma pp$  and  $pp$  systems; the photon energy scale is also shown. The different angles for the two reactions are chosen to match the momentum transfers, as discussed in the text. The shaded band is the HRM result, which is based on the  $pp$  elastic data.

$pn$  and the  $\gamma d \rightarrow pn$  data is insufficient to show if oscillations are indeed present for those reactions.

Brodsky and de Teramond [37] suggested that the oscillations and also the associated large values of the  $A_{NN}$  spin correlations observed in  $pp$  scattering [39] are due to the presence of broad resonances associated with the onset of the strangeness and charm thresholds in the intermediate state of the  $pp \rightarrow pp$  amplitude. If this is correct, then one would also expect to see similarly strong spin-spin correlations in the emerging proton pair at the corresponding invariant mass. The observation of the large cross sections predicted here then leads to important related polarization measurements. One also would expect the production of doubly-charged final states with baryon number  $B = 2$  containing charmed hadrons in  $\gamma^3\text{He} \rightarrow nX$  at missing mass  $m_X > 5$  GeV. The threshold for open charm production is  $\sqrt{s} > 6$  GeV,  $E_{\text{lab}}^\gamma = (s - M_{^3\text{He}}^2)/(2M_{^3\text{He}}) > 4.5$  GeV.

#### 4. The $\alpha_n$ distribution

The recoil neutron in  $\gamma^3\text{He} \rightarrow pp + n$  gives an additional degree of freedom for checking the underlying mechanism of hard  $pp$  pair production. The observable which is best suited for this purpose is the light-cone momentum distribution of the recoil neutron, defined as a function of  $\alpha_n = (E_n - p_n^z)/(m_{^3\text{He}}/3)$ . We use here light-cone variables in which the  $\alpha$ 's are defined as follows:

$$\alpha = A \frac{E^N - p_z^N}{E^A - p_z^A} \approx \frac{E_N - p_z^N}{m_N}, \quad (4)$$

where the  $z$  direction is chosen in the direction of the incident photon beam.

With the above definitions,  $\alpha$  for the incident photon is exactly zero, while  $\alpha$  for the  $^3\text{He}$  target is 3. Conservation of  $\alpha$  allows  $\alpha_n$  to be determined from the measurement of the light-cone fractions of the protons:

$$\alpha_\gamma + \alpha_{^3\text{He}} = 0 + 3 = \alpha_{p_1} + \alpha_{p_2} + \alpha_n. \quad (5)$$

Therefore:

$$\alpha_n = 3 - \alpha_{p_1} - \alpha_{p_2}. \quad (6)$$

An important feature of high-energy small-angle final-state rescattering is that it does not change the light-

cone fractions of the fast protons, see, e.g., [40]. As a result, the experimentally determined  $\alpha_n$  coincides with the value of  $\alpha_n$  in the initial state and unambiguously measures the light-cone fraction of the two-proton subsystem in the  ${}^3\text{He}$  wave function. Furthermore, in the  ${}^3\text{He}$  wave function the c.m. momentum distribution of the  $NN$  pair depends on the relative momentum of the nucleons in the pair, so one can probe the magnitude of the momentum in the  $pp$  pair involved in the hard disintegration.

To illustrate the sensitivity of the  $\alpha_n$  distribution to the mechanism of the high- $p_T$  disintegration of a  $pp$  pair, we compare in Fig. 4 the  $\alpha_n$  dependence of the differential cross section  $d\sigma/(dt d^2p_T d\alpha_n/\alpha_n)$  calculated in the framework of the RNA and HRM models. The calculations are done for a scattering of two protons in the final state at fixed initial photon energy  $E_\gamma = 4$  GeV and  $\theta_{\text{c.m.}} = 90^\circ$ . Within the RNA approximation (solid line), the  $\alpha_n$  distribution is calculated for configurations in which the relative transverse mo-

mentum of the  $pp$  pair is equal to the transverse momentum of the final protons  $p_T \sim \text{GeV}/c$ . The estimate within the HRM model is done using Eq. (3). In the latter case, the internal momenta in the  $pp$  pair contributing to the cross section are  $\leq 300 \text{ MeV}/c$ . The results presented in Fig. 4 provide substantially different predictions for the  $\alpha_n$  distribution. Qualitatively, the much broader distribution of  $\alpha_n$  in the RNA model is due to selection of large momenta of protons in the  ${}^3\text{He}$  wave function, which leads to a broader distribution of neutron momenta.

Another feature of the  $\alpha_n$  distribution is that the strong  $s$  dependence,  $\sim s^{-11}$ , of the hard disintegration cross section will tend to suppress (increase) the contribution from those values of  $\alpha_n$  which increase (decrease) the effective  $s_{pp} \approx 2E_\gamma M_d(3 - \alpha_n)/2 + M_d^2$  involved in the  $\gamma + pp$  subprocess. As a result one expects the  $\alpha$  distribution to be asymmetric about  $\alpha_n = 1$ . The extent of the asymmetry depends strongly on the exponent in the  $s$  dependence of hard disintegration cross section. To illustrate this phenomenon, in Fig. 4 we compare the  $\alpha_n$  distributions within the RNA and HRM models, rescaled in one case by  $s_{pp}^{11}$  (bold solid and dashed lines) and in other case by  $s_d^{11}$  ( $s_d = 2E_\gamma M_d + M_d^2$ ) (thin lines). This comparison demonstrates that the measurement of the  $\alpha_n$  asymmetry will give us an additional tool in verifying the energy ( $s$ ) dependence of the disintegration cross section.

## 5. Experiments

Data for  ${}^3\text{He}$  photodisintegration have already been obtained by the CLAS collaboration, up to energies of 1.5 GeV, but no results are available as yet [41]. As the onset of scaling in deuteron photodisintegration is just above 1 GeV, it will be interesting to see if there is a similar onset for  ${}^3\text{He}$ , and, if so, what is the ratio of  ${}^3\text{He}$  to deuteron photodisintegration cross sections.

Studying the  $\gamma {}^3\text{He} \rightarrow pp + n$  reaction to significantly higher energies requires measuring a small cross section reaction that generates two high transverse momentum protons. It is only possible in Hall A of the Thomas Jefferson National Accelerator Facility using Bremsstrahlung photons, produced by the electron beam passing through a photon radiator. The maximum energy of the Bremsstrahlung beam is essen-

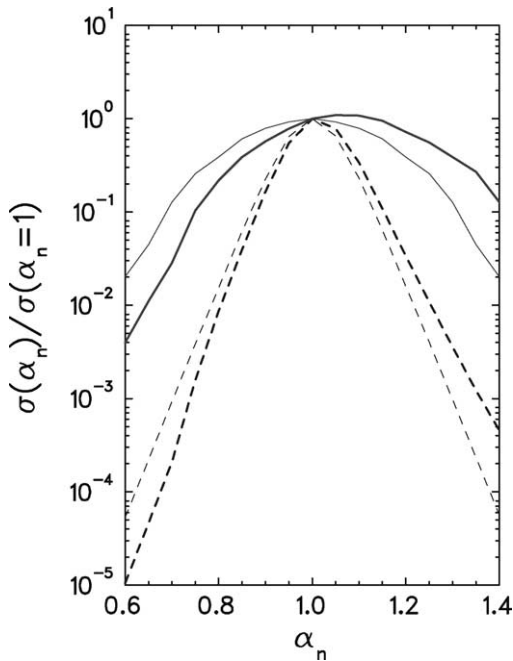


Fig. 4. The  $\alpha_n$  dependence of the  $\gamma {}^3\text{He} \rightarrow pp + n$  cross section calculated within RNA (bold solid line) and HRM (bold dashed line) models.  $\sigma(\alpha_n)$  corresponds to the differential cross section scaled by  $s_{pp}^{11}$ . Thin solid and dashed lines correspond to the same calculations scaled by  $s_d^{11}$ . All calculations are normalized to one at  $\alpha_n = 1$ .

tially equal to the incident electron kinetic energy. The two outgoing protons, each with about half the incident beam energy, can be detected in coincidence with the two existing high resolution spectrometers (HRS). The energy dependence of the differential cross section for  $\theta_{\text{c.m.}} \approx 90^\circ$  can be measured up to  $E_\gamma \approx 5$  GeV with the existing equipment, if the cross sections are as large as predicted here. In contrast, it has only been possible to measure deuteron photodisintegration up to 4 GeV at  $\theta_{\text{c.m.}} \approx 90^\circ$ , due to the rapid decrease of its cross section. If the large predicted cross sections are verified, polarization measurements will be possible to  $\approx 4$  GeV. A measurement of  $A_{NN}$  of the two outgoing protons would be particularly interesting in view of the observed dramatic spin effects in elastic  $pp \rightarrow pp$ , and will require a dedicated measurement with polarimeters in both spectrometers. With the proposed 12 GeV upgrade, including the proposed higher momentum spectrometer for Hall A, it would be possible to extend the measurements up to about 7 GeV in a matter of weeks, limited by the maximum momentum in the HRS spectrometer.

## 6. Summary and outlook

A unique signature of quark–gluon degrees of freedom in hard photodisintegration reactions is the prediction of a sizable cross section, larger for  $pp$  than for  $pn$  pairs. If the hard photodisintegration process can be factorized so that it depends on the  $NN$  scattering amplitude, then the oscillations apparent in  $pp$  scattering could be reflected in the measured cross sections. Comparing the predictions presented here to data could put our understanding of deuteron photodisintegration on a firmer basis, and would be a significant step toward a general understanding of hard nuclear photo-reactions at intermediate energies.

The observation of oscillations with energy would give us a new tool in studies of color coherence phenomena in hard nuclear reactions. The investigation of  $A$  dependence of the reaction extended to nuclei with  $A > 3$  would allow a study of the nature of these oscillations. For instance, if the oscillations are the result of the interplay of soft and hard scattering amplitudes, one expects more absorption for the soft part of the total amplitude—a phenomenon known as a nuclear filtering.

We also observe that determining the shape and the asymmetry of the  $\alpha_n$  distribution in the hard  $\gamma^3\text{He} \rightarrow pp + n$  reaction gives an additional experimental tool in studying the dynamics of the high energy disintegration of a  $NN$  pair.

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